CERN – European Organization for Nuclear Research
European Laboratory for Particle Physics

CLIC Note 431

Delayed RF breakdown in a microwave cavity

G. Geschonke and W. Schnell

Geneva, Switzerland
3 April 2000

23 March, 2000

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Observations

In the frame of the CLIC study a single-cell TM_{01} (pillbox) cavity (called HIGGS) is being pulse-excited to very high fields in order to study breakdown phenomena. The frequency is 30 GHz. Figures 1 and 2, which have been presented by H. Braun and W. Wuensch at the CLIC CTF meeting of 17th March 2000, sum up the experiment and the observations made.

Figure 2 shows the peak surface electric field as a function of time. The cavity is excited by a short pulse of relativistic electrons passing along the axis. This causes the initial rise of the field, followed by a free oscillation. Six pulses are superimposed. On each pulse the same surface field of about 0.66 GV/m is reached, followed by the same natural decay with time constant $2Q/\omega$. After a delay, which varies randomly from 10 ns to several tens of nanoseconds, the field "breaks down" rapidly, though apparently not instantaneously. The onset of break down occurs at less than the peak field. At the same field levels breakdown fails to occur if the initial peak is reduced. It is also observed that the oscillation frequency increases during the breakdown. There is no visible surface damage.

A model for delayed breakdown

A model for the observed phenomena has to explain the delay of breakdown, its dependence on the initial field rather than the field at which it occurs and the avalanche mechanism responsible for its occurrence. Such a model, involving the *RF heating of dust particles to run-away thermal emission*, is analyzed here. It has been proposed by G. G. and is suggested by the visual observation *in LEP cavities* of glowing dust particles, followed by the random occurrence of a flash of light and field breakdown. In LEP cavities such observations are relatively easy because of their large size and continuous-wave operation. In HIGGS the following situation may be assumed.

A dust particle of volume V and loss factor ($\tan\delta$) is exposed to the RF electric field E of frequency ω. It therefore absorbs a power $P = (\tan\delta)\omega W$ where $W = V\varepsilon_0\alpha E^2/2$ is the field energy within the dust particle. The form factor α may be taken equal to 3 (as for an infinitely conducting sphere in free space). If ρC_P is the dust particle's heat capacity per unit volume, the time delay to reach sufficient temperature T_E for thermal emission of electrons is given by

$$\Delta t = 2(\tan\delta)^{-1} T_E \rho C_P / (\omega\varepsilon_0\alpha\ \overline{E}^2)\ .$$

The volume of the particle cancels out! The following appears to be a set of plausible assumptions:

$\overline{E}^2 = (0.51\ \mathrm{GVm^{-1}})^2$

$\tan\delta = 1$

$\alpha = 3$

$\rho C_P = 1.5\times10^6\ \mathrm{Jm^{-3}K^{-1}}$

$T_E = 3500^0$K.

The mean square field was found by approximate integration of Fig. 2 from zero to the onset of breakdown at 10 ns, the rise and fall of field being taken as linear. The specific heat per unit volume is for carbon (in graphite form) or silicon (at room temperature). The temperature T_E is typical for a carbon arc. The assumed loss factor $\tan\delta$ appears to be a maximum (45^0 phase angle within the dust particle, as within a skin depth). This, and the implied assumption that the particle considered is located at maximum field, makes sure that the delay found is a minimum, except for the uncertainty in the form factor α. The result

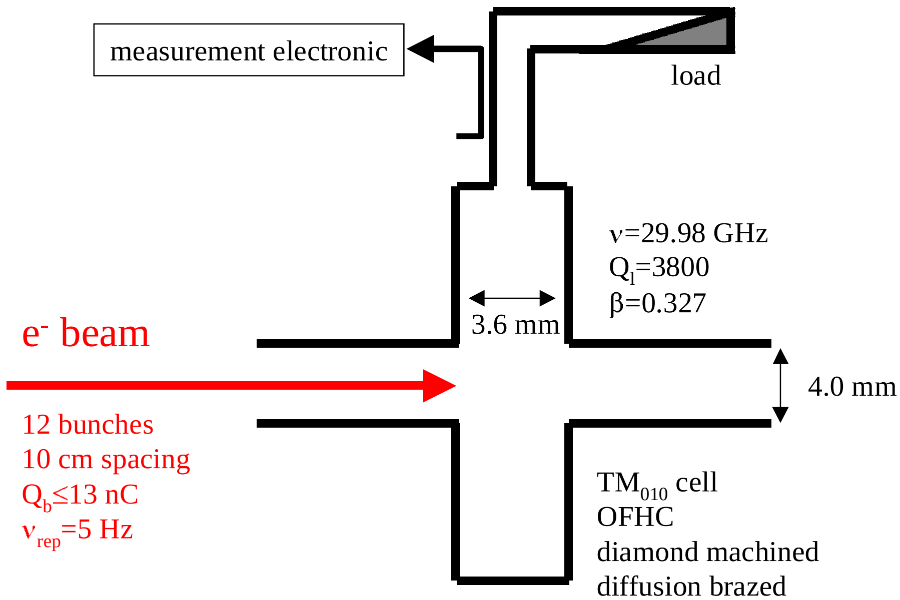
<u>$\Delta t = 8.1$ ns</u>

agrees with the observed minimum delay as well as one could possibly expect from such a rough model.

Once thermal electron emission has started, it will produce further dissipation and, thus, an avalanche effect, probably ending with the evaporation of the particle. The loading of the cavity by a large electron density during run-away emission creates the equivalent of a parallel inductance and, hence, an increase of oscillation frequency - in agreement with observation. If a dust particle has a slightly smaller loss factor, the field has time to decay further during the heating process and the onset of emission is much delayed, if not avoided altogether. This would explain the randomness of the delay beyond a minimum. If the peak field is reduced, the onset of emission is avoided for the same reason. The model also explains the absence of surface damage but suggests that prolonged "conditioning" as well as extreme cleanliness during assembly should be helpful.

Heat loss by radiation is assumed negligible here. In the case of the LEP cavities – where the product ωE^2 is five orders of magnitude lower – radiation cooling must be invoked to explain the visual observation of incandescent particles in stable (if precarious) equilibrium (which is finally upset by slow evaporation and associated reduction of surface to volume ratio).

HIGGS (=High Gradient Single Cell) Experiment



peak surface field	**observations**	**surface temperature rise (estimated)**
540 MV/m	no break downs	44 K
590 MV/m	onset of breakdowns	53 K
750 MV/m	break downs on every pulse, few ns after max. E(t)	85 K

Figure 1 Summary transparency of the HIGGS experiment.

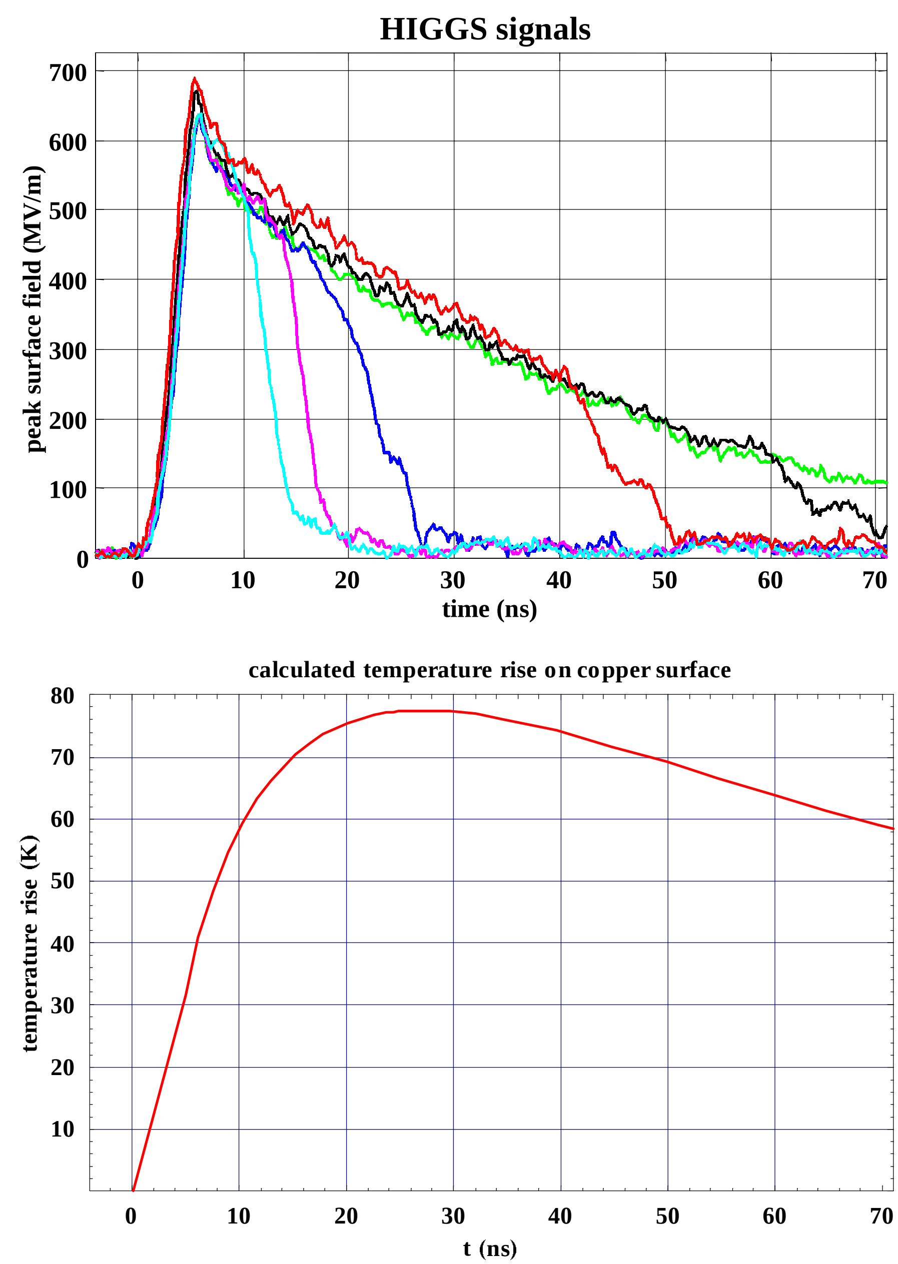


Figure 2 Upper graph: Enveloppes of the field amplitude in the HIGGS cavity, showing RF break-downs at different times.
Lower graph: computed surface temperature of HIGGS cavity at location of highest magnetic field.